Lasers in Surgery and Medicine 20:346–353 (1997)

Optimal Parameters for Laser Treatment of Leg Telangiectasia

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Background and Objective: **The optimal parameters for treatment of leg telangiectasia with a pulsed laser are investigated.**
Study Design/Materials and Methods: **The Monte Carlo method is used to calculate the light penetration and absorption in the epidermis, dermis, and the ectatic blood vessel. Calculations are made for different diameters and depths of the vessel in the dermis. In addition, the oxygen saturation of the blood vessel, the laser beam diameter, and the laser irradiation profile is varied.**
Results: **It is found that for vessels with diameters between 0.3 mm and 0.5 mm wavelengths about 600 nm are optimal to achieve selective photothermolysis for the considered damage model. It is also shown that an elliptical laser beam area has advantages compared to a circular beam area for treatment of leg telangiectasia.**
Conclusions: **We recommend the treatment of leg telangiectasia with dye laser wavelengths longer than the normally used 577 nm and 585 nm. Lasers Surg. Medicine 20:346–353, 1997.**
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Key words: blood vessel; dye laser; laser beam diameter/profile; Monte Carlo; telangiectasia; tissue optics

INTRODUCTION

Telangiectasia on the legs occur in about 35% of women and 10% of men in the United States [1]. The most common method for treating these cosmetically unattractive veins in the dermis is sclerotherapy. However, this therapy and other forms of treatment have negative side effects, e.g., postsclerosis pigmentation or telangiectatic matting [2].

As an alternative to sclerotherapy, laser treatment of leg telangiectasia has been investigated. Laser light is successfully used for benign cutaneous vascular ectasias, such as port wine stains, hemangiomas, spider nevi, or facial telangiectasias [3]. Contrarily, laser treatment of leg telangiectasia has not revealed adequate results. Although different lasers have been investigated, for example argon lasers or dye lasers, no satisfying outcome was obtained [3,4]. Only the treatment of vessels of small diameters with the dye laser [5] and using a cooling technique [6] produced good results.

For treatment of vascular malformations in the dermis, the laser parameters are chosen to obtain selective photothermolysis [7], a process whereby chromophores, in our case the hemoglobin in the vessels, are selectively damaged sparing the neighbouring tissue. This is achieved on the one side by applying a short laser pulse which should be smaller than the relaxation time of the blood vessel to avoid heat conduction to the surrounding tissue [8], and on the other side by choosing the wavelength of the laser to permit a large penetration depth into the skin and selective heating of the blood vessel. Several investigations have been conducted to determine the optimal parameters for port wine stains. With experimental and theoretical studies, it was found that the optimal wavelengths for treatment of port wine stains are about 580–590 nm [9–13]. Similar studies for leg telangiectasia could not be found in the literature.

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Accepted for publication 24 May 1996.

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Results for port wine stains cannot simply be transfered to leg telangiectasia, because the diameter of the ectatic vessels can be considerably greater and the oxygen saturation of the blood in the vessels of leg telangiectasia is smaller than in port wine stains vessels, for which 100% oxygen saturation is usually assumed [12]. Also, the blood content in the dermis is different. Therefore, the optimal parameters of the laser to achieve coagulation of the blood vessel change.

In this article, we investigate the optimal wavelength for treatment of ectatic veins in the dermis with different diameters and depths using Monte Carlo simulations. Wavelengths between 577 and 610 nm, which can be produced with dye lasers, are considered. The oxygen saturation of the blood in the vessel is altered to analyse the difference of the optimal wavelength for treating veins or arteries. We also investigate heat production in the ectatic vessel for variable diameters of the laser beam. This includes simulations of the difference between a circular and an elliptical beam profile.

MATERIALS AND METHODS

Monte Carlo Simulations

The Monte Carlo method is applied to calculate the light penetration and absorption in tissue [14,15]. The geometry used in the simulations is shown in Figure 1. (For a thorough description, see also [13].) A laser beam is incident perpendicular onto the turbid medium which consists of two layers. If not explicitly mentioned, the laser beam used in the simulations has a circular flat profile with a diameter $d = 4$ mm. The first layer is 0.06 mm and the second is infinitely thick representing the epidermis and the dermis, respectively. The Monte Carlo program simulates the vessel as a cylinder with a diameter D placed in the dermis at depth a below the tissue surface. The layers have infinite extensions in x- and y-directions, whereas the vessel is infinite in y-directions. The probability of absorption per mm^3 below the laser beam for an incident photon Δq is calculated vs. tissue depth. The temperature increase ΔT is proportional to Δq, if heat conduction can be neglected

$$\Delta T = \frac{E\Delta q}{\rho_d C}, \tag{1}$$

where E is the total incident pulse energy, ρ_d the density and C the specific heat of the tissue. This approximation is valid, if the duration of the laser pulse is smaller than the thermal relaxation time [8]. For example, the laser pulse lengths of the dye laser used in dermatology is less than about 0.5 μs. For this pulse length, heat conduction can be neglected for vessel sizes greater than D ≈ 0.03 mm. $\Delta q(z)$ is calculated at $x = 0$ and y-values between $-0.4d < y < 0.4d$ are averaged to improve the statistics of the simulations. (The origin of the co-ordinate system is in the center of the laser beam.)

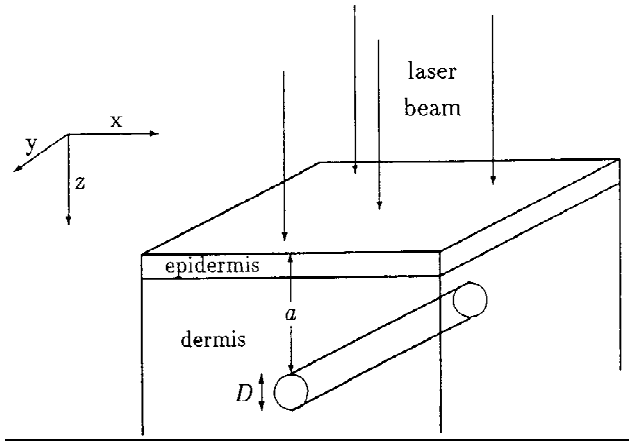

Fig. 1. Geometry of the Monte Carlo simulations.

For the determination of the optimal wavelength for selective photothermolysis $\Delta q(z)$ in the vessel Δq_v has to be greater than in the epidermis Δq_d. Because the exact mechanism which leads to the damage of the vessel is not known, several proposals were made for the calculations of Δq_v in the literature. For example, often Δq at the top of the vessel is used [11,12]. However, several studies showed indications that it is necessary to coagulate the whole vessel to damage the vessel irreversibly [16,17]. In this case, the smallest $\Delta q(z)$ value in the vessels has to be considered to predict what wavelength is optimal for selective photothermolysis. In this study, both models are discussed. The optimal wavelength is obtained when the ratio $\Delta q_v/\Delta q_d$ is maximal.

Simulations are shown for three vessel diameters $D = 0.1, 0.3, 0.5$ mm at a vessel depth of $a = 0.6$ mm and an oxygen saturation of 70% for $\lambda = 577, 585, 590, 600, 610$ nm (see Results). These wavelengths are also used in the Results section where first the depth of the vessel with $D = 0.3$ mm is changed to $a = 1.0$ mm, and second the oxygen saturation is altered to 100%. We also cal-

culate $\Delta q(z)$ for a vessel with $D = 0.3$ mm, $a = 0.6$ mm, and an oxygen saturation of 70% at 600 nm for the different laser diameters, d = 1, 2, 4, 6, 8 mm. Finally, we compare the distribution of absorbed photons in a vessel with the parameters of the Results section, "Beam Diameter" for a circular and an elliptical flat beam profile.

Optical Coefficients

A refractive index of 1.37 for all tissue types is used [11]. We apply 1.75 mm^{-1} for the reduced scattering coefficient $\mu'_s = \mu_s (1—g)$ of both the dermis and the epidermis, where μ_s represents the scattering coefficient and g the anisotropy factor. This value was determined by in vivo measurements on the human forearm using spatially resolved reflectance measurements and a multilayer model [13]. The anisotropy factor is assumed to be $g = 0.9$ for epidermis and dermis, and for blood, we use $g = 0.995$ [18]. The absorption coefficient μ_a of epidermis and bloodless dermis is set to $\mu_a = 0.8$ mm^{-1} and $\mu_a = 0.015$ mm^{-1}, respectively [13]. These values are used for all considered wavelengths between 577 and 610 nm [13].

The values of the optical parameters of blood can be seen in Table 1 [11,18]. The oxygen saturation of leg telangiectasia was measured, on the upper thigh of a female using a blood gas analysis apparatus, as 71.6%. The leg vein was punctured with a needle and the blood was taken up with a glass capillary. With the blood gas analysis apparatus, the oxygen tension was measured with a standard method using chemical reactions at an electrode. From this, the oxygen saturation was calculated using the known relationship between blood oxygen saturation and blood oxygen tension. The measured value corresponds to the oxygen saturation of venous blood found in textbooks [19]. Thus, for the calculations of leg telangiectasia, an oxygen saturation of 70% was assumed for the blood in the ectatic vessel. The absorption coefficient of blood with 70% oxygen saturation was calculated from data of Kampen and Zilstra [20] as used in Ref. [11], see Table 1. We assume a volumetric blood content of 1% in the dermis. Therefore, the absorption coefficient of the dermis containing blood is changed according to the volumetric percentage of blood in the dermis [13]. The resulting values can be seen in Table 1. Oxyhemoglobin is assumed for the blood in the dermis.

TABLE 1. The Scattering Coefficient of Blood and the Absorption Coefficient of Blood With 100% and 70% Oxygen Saturation and of Dermis*

λ [nm]	μ_s^{blood} [mm^{-1}]	$\mu_a^{blood,100\%}$ [mm^{-1}]	$\mu_a^{blood,70\%}$ [mm^{-1}]	$\mu_a^{dermis,1\%}$ [mm^{-1}]
577	46.8	35.4	31.4	0.37
585	46.7	19.1	18.6	0.21
590	46.6	6.9	9.1	0.084
600	46.4	2.5	4.0	0.04
610	46.4	1.2	2.0	0.027

*For the dermis, a blood volume concentration of 1% is assumed.

RESULTS

Vessel Diameters

In this section, an ectatic venous vessel with an oxygen saturation of 70% at a depth $a = 0.6$ mm is considered. Figures 2–4 show $\Delta q(z)$ for $D = 0.1$, 0.3, 0.5 mm. Several characteristics are common in these figures. In general, the highest values of $\Delta q(z)$, and hence of the temperature, are in the epidermis and in the vessel, because μ_a of blood and epidermis is greater than μ_a of dermis. The vessel at $a = 0.6$ mm does not noticeably influence $\Delta q(z)$ in the epidermis for all diameters of the vessels. $\Delta q(z)$ in the epidermis increases for longer wavelengths. The reason for the latter is that μ_a of the dermis decreases for longer wavelengths (see Table 1), thus, the amount of backscattered light to the epidermis and hence $\Delta q(z)$ is increased. At the top of the vessel (at $a = 0.6$ mm) $\Delta q(z)$ depends only to a small amount on the vessel diameter. That means, if only a local high temperature is needed to damage the vessel reversibly, the vessel diameter does not affect the therapeutic outcome to a great amount.

Figures 2–4 show that $\Delta q(z)$ in the vessel decreases faster for shorter wavelengths, because the absorption coefficient increases. The increase at the bottom of the vessels seen especially at smaller wavelengths is due to photons entering the vessel from the bottom or laterally. If the lowest value of $\Delta q(z)$ in the vessel at a certain wavelength is used as damage criterion, Figure 2 shows that for the vessel with $D = 0.1$ mm wavelengths between 585 nm and 590 nm are optimal, that means there the ratio $\Delta q_v/\Delta q_d$ has its greatest value. For $D = 0.3$ mm and $D = 0.5$ mm, see Figures 3 and 4, the optimal wavelength using this assumption is 600 nm and between 600 nm and 610 nm, respectively.

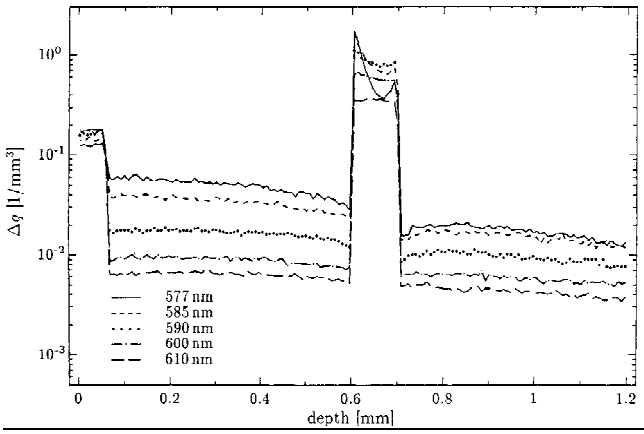

Fig. 2. Δq as a function of the depth in the tissue for the wavelengths 577 nm, 585 nm, 590 nm, 600 nm, and 610 nm. The vessel has a diameter of 0.1 mm and is located at $a = 0.6$ mm. The oxygen saturation of the blood in the vessel is 70%.

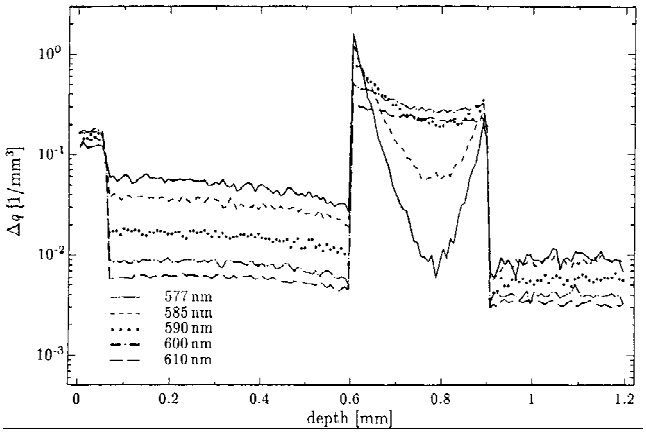

Fig. 3. Δq as a function of the depth in the tissue for the wavelengths 577 nm, 585 nm, 590 nm, 600 nm, and 610 nm. The vessel has a diameter of 0.3 mm and is located at $a = 0.6$ mm. The oxygen saturation of the blood in the vessel is 70%.

Oxygen Saturation

In this section, we investigate how the oxygen saturation of the blood in the vessel changes the optimal wavelength for laser treatment. Figure 5 shows a vessel at a depth $a = 0.6$ mm, with diameter $D = 0.3$ mm, and an oxygen saturation of 100%. Thus, this vessel represents a telangiectasia in the face [12]. If Figure 5 is compared to Figure 3, which shows a vessel with the same geometrical parameters but an oxygen saturation of 70%, it can be stated that the optimal wavelength is shifted from $\lambda = 600$ nm to wavelengths between $\lambda = 590$ nm and $\lambda = 600$ nm using the lowest $\Delta q(z)$ value criterion in the vessel. This is because μ_a of blood with 70% oxygen saturation at

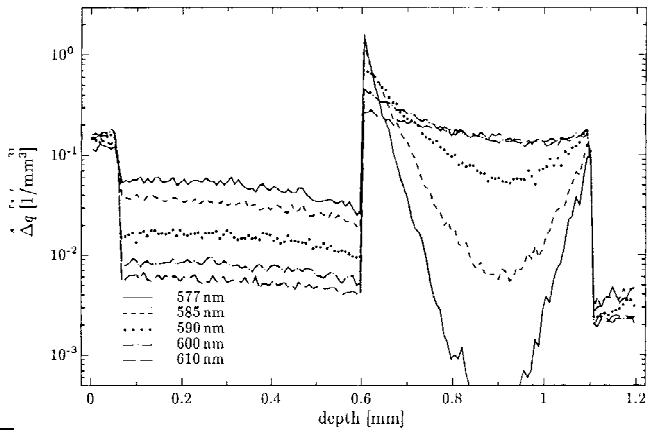

Fig. 4. Δq as a function of the depth in the tissue for the wavelengths 577 nm, 585 nm, 590 nm, 600 nm, and 610 nm. The vessel has a diameter of 0.5 mm and is located at $a = 0.6$ mm. The oxygen saturation of the blood in the vessel is 70%.

$\lambda = 600$ nm equals μ_a of blood with an oxygen saturation of 100% at about $\lambda = 595$ nm.

Vessel Depth

For the figures shown so far, the depth of the vessel was $a = 0.6$ mm. Figure 6 gives a vessel with 70% oxygen saturation and a diameter $D = 0.3$ mm as in Figure 3, but the vessel depth is changed to $a = 1.0$ mm. As expected, the absolute values of $\Delta q(z)$ in the vessel decrease for all wavelengths if the vessel depth is increased (compare Figs. 3 and 6). The optimal wavelength using the criterion of the lowest value of $\Delta q(z)$ in the vessel is about 600 nm as for the vessel at $a = 0.6$ mm; see Figure 3. However, a small shift towards longer optimal wavelengths can be seen for the vessel in Figure 6 compared to the vessel in Figure 3, if the curves at $\lambda = 590$ nm and $\lambda = 610$ nm in these figures are compared. This is due to the fact that $\Delta q(z)$ in the dermis decreases faster with increasing depths for shorter wavelengths compared to longer wavelengths, because the absorption coefficient is greater at shorter wavelengths. Nevertheless, this wavelength shift is not pronounced, because the absorption coefficient at wavelengths about $\lambda = 600$ nm is relatively small. Thus, in the case of leg telangiectasia, the depth of the vessel is not as important as for port wine stains, where the dermis contains more blood and hence the absorption coefficient is greater.

Beam Diameter

In this section, the dependence of selective photothermolysis on the diameter of the laser

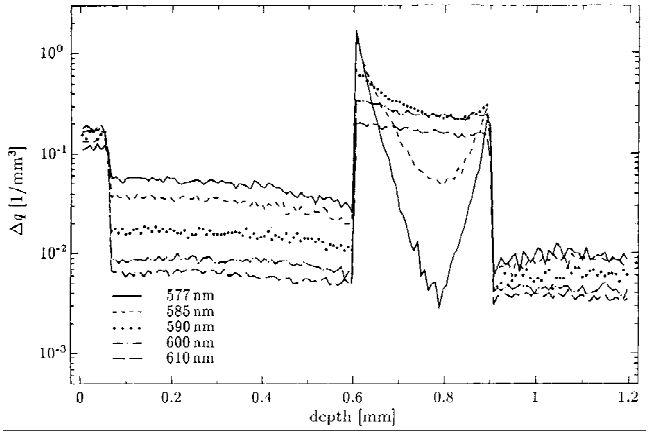

Fig. 5. Δq as a function of the depth in the tissue for the wavelengths 577 nm, 585 nm, 590 nm, 600 nm, and 610 nm. The vessel has a diameter of 0.1 mm and is located at $a = 0.6$ mm. The oxygen saturation in the blood of the vessel is 100%.

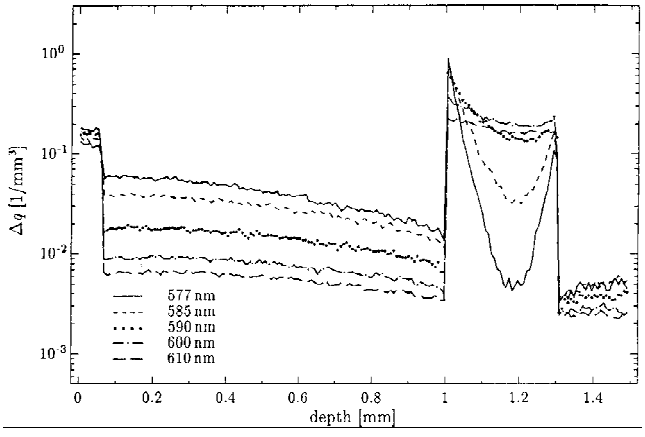

Fig. 6. Δq as a function of the depth in the tissue for the wavelengths 577 nm, 585 nm, 590 nm, 600 nm, and 610 nm. The vessel has a diameter of 0.3 mm. The oxygen saturation in the blood of the vessel is 70%. The depth of the blood vessel is $a = 1.0$ mm.

beam is presented. The intensity of the laser beam is chosen to be constant for all laser diameters. In order to compare the temperature response of the tissue for different diameters, the use of $\Delta q(z)$ is not favourable, because ΔT in the tissue is proportional to $E\Delta q(z)$, see Eq. 1. Therefore, the area of the laser beam has to be considered. We define a new quantity $\Delta q(z)'$, which is proportional to ΔT and equals $\Delta q(z)$ for a beam with a diameter of $d = 4$ mm:

$$\Delta q(z) = \Delta q(z)\,\frac{d^2[\mathrm{mm}]}{4^2\mathrm{mm}}. \qquad (2)$$

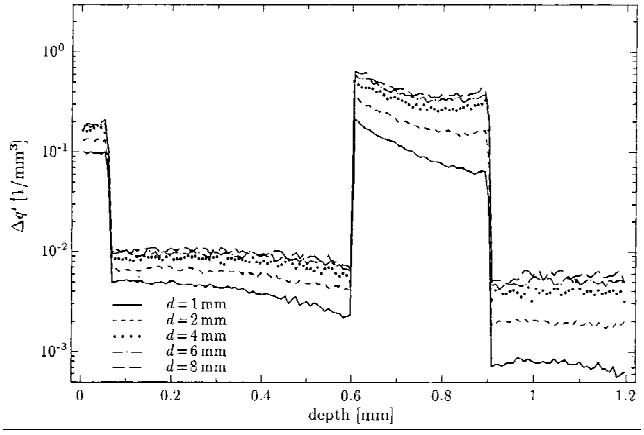

Fig. 7. $\Delta q'$ as a function of the depth in the tissue at 600 nm. The vessel has a diameter of 0.3 mm. The oxygen saturation in the blood of the vessel is 70%. The depth of the blood vessel is $a = 0.6$ mm. The diameters of the circular flat beam are $d = 1, 2, 4, 6, 8$ mm.

Figure 7 shows a vessel at $a = 0.6$ mm with a diameter $D = 0.3$ mm and an oxygen saturation of 70% at a wavelength of $\lambda = 600$ nm. The diameters of the laser beam with a flat beam profile are $d = 1, 2, 4, 6, 8$ mm. In Figure 7, it can be seen that $\Delta q'(z)$ decreases faster with increasing tissue depths if the beam diameter is smaller. For example, at the bottom of the vessel $\Delta q'(z)$ for $d = 8$ mm is about seven times greater than for $d = 1$ mm, whereas at the epidermis $\Delta q'(z)$ is only two times greater. This means that selective photothermolysis can be better achieved using greater diameters of the laser beam provided that the intensity of the incident beam is the same. However, if the diameter is larger, more laser energy is needed and in addition the risk of negative side effects is greater, because, even if Δq in the epidermis is the same, the probability of an undesirable damage of the epidermis is proportional to the area of the laser beam.

Circular and Elliptical Flat Beam Profile

In order to investigate whether it is possible to minimize the probability of negative side effects, the difference of a circular and an elliptical flat beam profile is investigated in this section. The great diameter (parallel to the vessel in y-direction, see Fig. 1) and the short diameter (parallel to the x-direction) of the elliptical beam are chosen to be 4 mm and 2 mm, respectively. The elliptical beam is compared to a circular beam with the same area. Thus, the diameter of the circular beam is 2.82 mm. To reduce the compu-

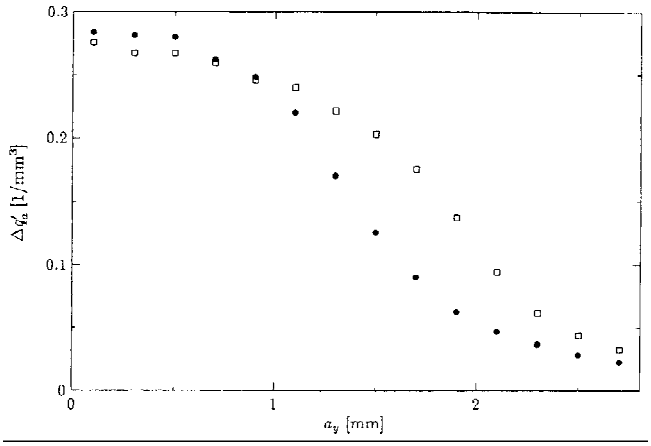

Fig. 8. $\Delta q'_a$ in the vessel as a function of the distance in y-direction from the center of the laser beam for a circular (solid circles) and an elliptical flat laser beam (open squares). The calculations are for $\lambda = 600$ nm and a vessel diameter of 0.3 mm. The oxygen saturation in the blood of the vessel is 70%. The depth of the blood vessel is $a = 0.6$ mm.

tation time, all $\Delta q'(z)$ with constant y values in the vessel (and $x = 0$ mm) are summarized yielding the quantity $\Delta q'_a$. Figure 8 shows $\Delta q'_a$ for these beam profiles as a function of the distance in y-direction from the center of the laser beam a_y for the same vessel as in the "Beam Diameter" section. At small a_y values, that means near the center of the beam, $\Delta q'_a$ is nearly the same for both beam profiles. $\Delta q'_a$ for the circular beam is somewhat greater, because the average distance of the incident photons from the vessel at $a_y = 0$ is smaller for the circular beam compared to the elliptical beam. As expected, $\Delta q'_a$ decreases faster for greater distances a_y in the case of the circular beam. Therefore, a greater part of the vessel can be coagulated with the elliptical beam and hence using the elliptical beam, less pulses are necessary to treat the vessel along its whole length. In addition, the treated area in x-direction is smaller for the elliptical beam compared to the circular beam minimizing the probability of negative side effects.

DISCUSSION

The probability of absorption per mm³ for an incident photon Δq was calculated vs. tissue depth for different diameters, depths, and oxygen saturations of an ectatic vessel. In order to obtain from these simulations the optimal wavelength for treatment of leg telangiectasia, the precise processes which lead to the damage of the blood vessel have to be known. $\Delta q(z)$ values on different locations of the vessel have been proposed in the literature to calculate the optimal wavelengths. If $\Delta q(z)$ on the top of the vessel is decisive for the damage of the vessel, the calculations show that the optimal wavelength does not depend on the geometry of the vessel to a great amount and $\lambda = 577$ nm is the optimal wavelength for all vessels simulated in this study. However, investigations show that the whole vessel has to be coagulated to achieve an irreversible damage [16,17]. In this case, we calculated that wavelengths about $\lambda = 600$ nm are a good compromise for the treatments of vessels with diameters between 0.3–0.5 mm. These findings are confirmed by Goldman et al. [21], who stated that for the fragile bluish telangiectasia of an elderly patient, "the 600 nm flash pumped dye laser treatments gave deeper clinical and microscopic reactions in these vessels than did the 585 nm laser treatments." In agreement with this clinical observation in our calculations, there is a great difference of the lowest temperature increase in the vessel at $\lambda = 600$ nm compared to $\lambda = 585$ nm. For example, in Figure 5, Δq at $\lambda = 600$ nm in the center of the vessel is five times greater than at $\lambda = 585$ nm and even thirty times greater than at $\lambda = 577$ nm.

In a recent article, we used the criterion that the average $\Delta q(z)$ in the whole vessel is crucial for the response of the vessel [13]. With this criterion, the optimal wavelength for each vessel is between the values obtained with the two criteria used above. For example, for this model, the optimal wavelength for the vessel in Figure 3 is about $\lambda = 590$ nm.

It was also pointed out that the optimal wavelength does not depend on the depth of the vessel in the dermis to a great amount for the optical parameters used in the simulations. In addition, it was shown that a greater oxygen saturation in the vessel shifts the optimal wavelengths to shorter values.

Regarding the diameters of the vessels used for the simulations, one has to be aware that the apparent diameter seen through the skin is considerably greater due to light scattering in tissue. It was calculated that a vessel with $D = 0.5$ mm at $a = 0.5$ mm appears to have a diameter which is about three times greater than its real diameter [22]. Thus, for example, the vessel shown in Figure 4 should have an apparent diameter of about 2 mm.

Simulations of different laser beam diameters showed that the ratio $\Delta q_v/\Delta q_d$ in the vessel

increases with increasing diameters of the beam provided that the intensity of the laser beam is constant and the smallest $\Delta q(z)$ value in the vessel is used as Δq_v. However, this increase is smaller at great diameters. Thus, diameters of about 4–6 mm used, for example, for treatment of port wine stains are a good compromize considering that the energy of the laser beam has to be increased with the square of the diameter.

For the treatment of leg telangiectasia, it has to be considered that a part of the laser beam is incident on normal skin tissue. Because this part is greater the larger the laser beam diameter, the probability of negative side effects on the normal tissue is increased using greater diameters. We showed that an elliptical area of the beam profile has the advantage compared to a circular area, that the number of pulses for the treatment of a vessel and the potential side effects can be reduced.

Note that there might exist other mechanisms than the distribution of the absorbed photons, and hence of the temperature in the tissue, which could influence the therapeutical results of leg telangiectasia treatments. Kimel et al. [17] reported that arterioles show higher vulnerability for thermal injury as compared to venules, although for the wavelength used in their study, the absorption coefficient of hemoglobin and oxyhemoglobin is the same. They argued that the reason for this might be that "blood clots can be transported downstream in venules, but not in arterioles since they get blocked in the capillaries."

Besides the wavelength, the pulse duration is also an important factor for treatment. In order to achieve maximum temperature increase within the vessel, heat loss during the laser pulse must be prevented. To estimate the time scale in which heat transfer to the surrounding tissue is important, usually the thermal relaxation time τ for vessels derived by Anderson and Parrish [7] is applied. For the large vessels in telangiectasia, this thermal relaxation time is rather long: e.g., for $D = 0.3$ mm we get $\tau \approx 45$ ms, compared to $\tau \approx 5$ ms for a vessel with $D = 0.1$ mm [7] which is typical for port wine stains. If the pulse duration is considerably smaller than τ, heat conduction during the pulse is negligible and the calculated values for Δq are proportional to the temperature increase ΔT at the end of the pulse. The pulse length of flashlamp pumped dye lasers commercially available is in the range of 0.1 to 0.5 ms, about two orders of magnitude smaller than τ for large ectatic vessels. So laser pulses are much shorter than needed for maximal vessel heating. In order to minimize damage to the epidermis, a pulse duration as long as technically possible (< 10ms) is recommended. In addition, this would also avoid damage to the small vessels in the normal skin and should, consequently, reduce the purpura seen after dye laser treatments.

In this study, wavelengths between 577 nm and 610 nm were considered. Although the absorption of blood is relatively small at longer wavelengths, it might be possible that wavelengths between 700 nm and 1100 nm show better treatment results (especially for deep and thick vessels) because the penetration depth is greater and the absorption of other chromophores (e.g., melanin) is smaller compared to wavelengths about 600 nm.

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